UCRL- 83941
PREPRINT

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This paper was prepared for submittal to Symposium on Energy and Ecology in the West, Tucson, Arizona, AIBS/ECS.

August 4, 1980

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Abstract. Geothermal power plants have the potential for supplying about 5% of the U.S. electrical generating needs by 1985, and are even now supplying about one third of San Francisco's electricity. Our investigations have shown that the typical geothermal field, such as the hot water resource of Imperial Valley, can be developed in an environmentally sound manner when proper considerations are made for ecosystem problems. We present experimental evidence pro and con for potential impacts due to habitat disturbance, powerline corridors, noise effects, trace element emissions from cooling towers, accidental brine discharges into aquatic or soil systems, competition for water and H_2S effects on vegetation. We recommend a mitigation and control strategy for each ecological issue and show where effects are likely to be irreversible. This evidence is the result of a continuing field ecology program initiated in 1975 and addressing geothermal development in the West, under the sponsorship of the Assistant Secretary for Environment, Department of Energy.

Key Words: geothermal impacts; geothermal brines; geothermal emissions, hydrogen sulfide; boron; sulfates; aquatic ecology; terrestrial ecology.

INTRODUCTION

Geothermal development in California has preceded that in other states and set the example for determining the potential impacts of geothermal power plants in the western U.S. Dry steam resources at The Geysers, California, already produce about 1000 MW of electrical power, and will eventually exceed 2000 MW, or about the same as a typical nuclear-power plant (Pacific Gas and Electric 1978). But the more common resource in the West is the hydrothermal type, characterized by hot brines with a total potential of about 20,000 MW of electrical power over 30 years (Muffler, 1979). The hydrothermal resources of California are found chiefly in the Imperial Valley, where power plant development is presently underway. The Geysers is comprised of both steam and hydrothermal resources and the latter is estimated to more than double the electrical production. Just across the border, Mexico operates a successful 75 MW geothermal power plant at Cerro Prieto.

There are several options for hydrothermal-electrical energy conversion, but all produce a spent brine residual, which must be injected back into the earth both to dispose of the huge quantities and to replenish the fluid reservoir. Geothermal power plants are unique among electrical production units in that they are typically small (50 MW), dispersed throughout the resource area, and must convert the resource to electricity _in situ_. Each power plant is small to minimize energy losses in pipelines, and about 20 wells supply 1.5 x 10^6 kg of fluids (hydrothermal) each hour per 50 MW (Layton and Pimentel 1980).

Out studies under sponsorship of the Department of Energy, were started in 1975 to determine the potential impact of geothermal development on ecosystems and to recommend control and mitigation of any potential impacts _prior_ to development. An integrated, interdisciplinary study was completed (Shinn et al. 1979) by the Imperial Valley Environmental Program (IVEP) and follow-on studies are being conducted at The Geysers and Imperial Valley, California, and at the Baca Location, New Mexico.

This presentation discusses the key ecological issues of geothermal development in California, the lessons learned, and some of our recommendations for mitigation.

HABITAT DISTURBANCE

A recurrent problem of geothermal power plant siting is the result of displacement and destruction of habitat. Since each power plant is typically served by 20 wells, a network of roads and drillpads must be established, followed by a brief, but disruptive drilling phase and by construction and maintenance of a pipeline network usually following the roads. The total land area occupied by the pipeline-road network will be small (less than 5%) but may cut avenues in animal migrating and feeding routes.

At the Salton Sea, where waterfowl and shorebirds coexist with geothermal development, we found that critical habitat of the Yuma clapper rail depended upon the cover of cattails and bulrush, the population of crayfish, and the slope of the steam banks (Bennett and Ohmart, 1978). Development there must be excluded except possibly by slant drilling or similar avoidance methods, but mitigation and improvement of existing habitat could be easily managed by maintaining non-fluctuating water levels and by providing crayfish habitat and nesting cover during the breeding season from March through October. At older geothermal developments, animal migration routes and other animal activities tend to return to normal after the construction phase except near heavy traffic areas. Noise effects from hydrothermal power plants will not be a problem. Measurements of sound pressure levels (SPL) by Leitner (unpublished) showed that drilling operations will not exceed 80 dBA at a distance of 15 m. Noise levels during normal operations are also well-known (Leitner, 1978), so that in general, the SPL should drop off to 54 dBA or less within 300 m. Such levels produce little change in animal behavior and do not interfere with bird calls, etc. An exception to this occurs at the rare, dry-steam developments such as The Geysers, where occasional venting of wells occurs at sonic velocities requiring that mufflers be installed.

Powerline corridors are another disturbance because the power plants tend to be located in remote areas. Leitner and Grant (1978) found that within 1.6 km of the Salton Sea, the traffic of migratory waterfowl and birds between roosting and feeding areas overlapped many altitude zones depending on species and weather conditions, implying a potential for collisions or for disrupting feeding and roosting area usage. Furthermore, birds such as cattle egrets tended to follow the river courses suggesting special powerline construction should be considered at river crossings.

The construction of a road and pipeline network also required special management practice to avoid extensive erosion which results in stream sedimentation and loss of aquatic habitat. The maintenance of a healthy aquatic ecosystem is threatened by erosion, water diversions, physical obstruction of fish and vertebrate migration and increased siltation. The effects of siltation on fish spawning, benthic invertebrates, and water quality in general have been well documented. In desert ecosystems, Romney et al. (1977) found that the initial geothermal construction disturbance resulted in such slow recovery in desert community relations that the land-use was essentially a "write-off" for ecosystems. But the effects of construction and development are usually very localized in the desert so that the percentage of land use lost may be small and insignificant.

INADVERTANT BRINE SPILLS

The chemical constituents of the hot brines varies considerably from site to site, dominated by NaCl, $CaCO_3$, and KCl, but the brines contain a host of minor elements in various degrees of speciation depending upon pH and dilution (Sposito, Page, and Mattigod, 1979). Accidental brine spills are of course possible, even though dikes and other precautions are taken, because of corrosion and high pressure in the pipelines. Layton and Morris (1980) estimate that a spill of the entire fluid flow of a 50 MW power plant for a duration of 45 min would amount to 1300 m^3 (1.0 acre-feet) discharged. Sposito et al. (1979) using a computerized model, GEOCHEM, calculated the resulting speciation of trace metals from typical brines discharged upon representative soils and surface waters and found that significant changes in biological availability occurred for toxic metals such as Ni, Cu, Zn, and Pb. Other toxic elements such as B also remain in solution. Our soil column leaching studies by G. Tompkins and R. Hung (unpublished) confirmed that brine caused release of large amounts of Cl, Pb, B, Cu, and Zn which were not originally in the brine itself. We estimated that a geothermal brine spill on most Imperial Valley soils would effectively result in loss of that land to agricultural use. Jury and Weeks (1977) found that it would take 3-10 years to reclaim those soils by leaching the brine unless the spill occurs immediately above a tile drain, which would require 1-3 years to leach.

The effects of an inadvertant brine spill would be long term in addition to the initial thermal and salinity shock. For aquatic systems, we (Ireland) developed a relative toxicity index and found that after initial salinity shock, the most toxic ions of Imperial Valley geothermal brine were, in order of toxicity; NH_4, B, Li, Mn, and Zn. Pb and Cu were practically insignificant. In Ireland's aquatic studies, mollies (Poecilia latipinna) had a cumulative mortality of 40% when exposed to 5% geothermal brine in Salton Sea water (22,000 ppm TDS) for two weeks. Pileworms (Neathes succinea), which are the foundation of the Salton Sea food chain, withstood a 5% geothermal brine added to Salton Sea water for 30 hours (LT_{50}), 1% brine for 13 days, and 0.5% brine for 22 days. G. Tompkins and R. Hung (unpublished) in our laboratory found that geothermal brine applied to the soils is more toxic to sugar beets and tomato than a NaCl solution of the same concentration, and significant increases of Se, Br, and other trace elements appeared in the leaves.

COOLING TOWER DRIFT

Long-term, chronic ecosystem exposure can result from downwind deposition of the heavily-mineralized, cooling-tower drift. For various reasons (Layton and Morris, 1980), geothermal power plants will contaminate their own cooling tower water with steam condensate and other residuals containing trace amounts of B, NH_3, SO_4, and heavy metals. Emission rates vary greatly. For example, the maximum 50 MW cooling-tower emission of boron at The Geysers is 2300 kg/yr, which compares with 77 kg/yr estimated at the Salton Sea hydrothermal resource according to Layton and Morris (1980). (Ammonia emission is usually greater than B emission; metals such as Hg and As are more than a 1000 times less.) These emissions can be reduced by efficient drift eliminators. Damage to vegetation due to boron deposition has been observed at The Geysers close-in to power plants (Malloch, Eaton, and Crane 1979). Usually, areas showing injury are not extensive, but evidence exists that measurable deposition occurs at greater distances and may contribute significant amounts of trace elements to watersheds. Koranda (1980) found that cooling tower drift deposited 5 μg/day of B on passive collectors at a distance of 120 m downwind of a power plant, where nearby barley plants retained a boron deposition of 2.4 μg per gram of dry matter. The same passive collectors also had retained 75% as much B at a distance of 1200 m as at the 120 m distance in one 21-day period. This longer-range deposition was also evident in the watersheds surrounding The Geysers power plants according to Ireland and Carter (in press). They measured NH_3, B, SO_4, and K runoff at the tributaries of downwind watersheds and found they could associate a chemical signature of power plant deposition at the periods of flow characterizing dry season, first rain, and peak flushing. The ecologically important emissions were B and NH_3, since B is toxic to plants and ammonia is toxic to aquatic organisms. Robertson _et al_. (1978) have measured geothermal emissions of Hg and As and found that although detectable, both are usually in a biologically unavailable state after emission. At The Geysers, Hg and As are negligibly increased over background levels in soil samples close to geothermal plants. At present, we can say only that the long-term exposure should be assessed on a case by case basis. At The Geysers, the deposition of trace elements and runoff to streams may be insignificant in the context of the historically complex geochemistry of the area. At Imperial Valley, the agricultural practices introduce trace elements from pesticides, herbicides, and fertilizers, with continued leaching of the soil by flood irrigation such that geothermal trace element depositions will be trivial by comparison.

VAPOR EMISSIONS

The noncondensable vapor emissions of geothermal steam usually consist of about 80% CO_2 and small amounts of H_2S, H_2, CH_4, N_2, and NH_3 as well as minor trace gases (Axtmann, 1975). The emissions of geothermal air pollutants are sufficient to cause some environmental concern, although installation of H_2S abatement is likely at most development sites because of the odor nuisance. The most biologically important gases are CO_2 and H_2S. Carbon dioxide is the limiting factor for photosynthesis if light, moisture, temperature, and nutrients are optimum. Although H_2S carries an essential element for plants, it is phytotoxic at high concentrations (Shinn et al. 1976). Potential air pollution effects due to geothermal development were studied extensively on the IVEP project (Shinn et al. 1979). Kercher (1977) developed a model by which photosynthesis and growth effects were investigated based on experimental bioassay dose-response data with mixtures of gases. The H_2S threshold-concentration for loss of dry matter production (growth injury, Thompson and Kats 1977, 1978) is an order of magnitude lower than for photosynthesis (Shinn et al. 1976, Coyne and Bingham, 1978). At low concentrations, H_2S stimulates growth of crops but at 0.3 ppm H_2S a significant reduction of growth occurs for lettuce, alfalfa, and cotton when the exposures are continuous, 24 hours a day. The threshold for injury to Imperial Valley crops under these worst case conditions is about a factor of ten higher than the California Air Quality standard of 0.03 ppm H_2S. It was also found, however, that the presence of increased CO_2 ameliorates the toxic effect of H_2S. On the other hand, 0.3 ppm H_2S + 50 ppm CO_2 increased the mortality and decreased the lifespan of honeybees, which may be significant if pollination is a limiting factor to seed production (Atkins, 1979).

We found that for nearly any geothermal development scenario envisioned, and considering the requirement for H_2S abatement because of the noxious odor, there will unlikely be any significant ecological effects of H_2S.

WATER RESOURCES AND WATER MANAGEMENT

Competition for water in the arid western U.S. is a problem for geothermal power plants in certain cases. Layton and Morris (1980) have assessed this problem quantitatively. The spent brines, about 2000 to 6500 metric tons per hour for a 50 MW plant, will be disposed by injection back to an underground reservoir. But in addition, the low thermal efficiencies of geothermal power results in large requirements for cooling water, more than four times the amount of cooling water required per unit of electricity for coal-fired power plants. Geothermal power plants can use waste waters for cooling such as irrigation tail-gate water or other brackish water. In return, the steam condensate is relatively pure and may be exchanged for lesser quality water. At The Geysers, which is a dry steam resource, there is little water required because the steam condensate is used for cooling tower make-up water and all residual water is injected at depth. At hydrothermal sites, development can proceed only after extensive water management procedures are worked out with water regulating agencies, such as the case with the Imperial Valley Irrigation District. The secondary problems for water management are the disposal of cooling tower blowdown sludges and separated wastes, as well as the requirement for an evaporation pond (Layton and Morris, 1980). Because geothermal power produces water from condensation and brines, there are many more options and trade-offs possible which have to be assessed on a site specific basis.

CONCLUSIONS

Experience with the early development phase of geothermal power has shown that habitat disturbance, inadvertant brine spills, cooling tower drift, vapor (H_2S) emissions, and water resources management are the important issues. We have presented a summary here of our field investigations determining the extent of these potential impacts and recommending mitigation measures which would aid the continued development of geothermal energy in an environmentally sound manner.

"Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48".

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